

Tabulation of Age Relationships of Bedrock
Units in the Middlesex Fells Reservation

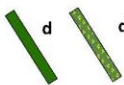
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Summary of Bedrock Stratigraphy

Last update: December 10, 2023

238 Ma **Trm** Medford Dike – NNE-SSW trending gabbro dike. Age (Ma): 238.07 ± 0.09 (U-Pb zircon CA-TIMS)

----- Time gap, Medford Dike crosscuts all dikes below -----



d **dp** Dolerite and basalt dikes (d), porphyritic dolerite and basalt dikes (dp) – numerous ages from Neoproterozoic to possibly early Triassic, offset by faults and crosscut each other, youngest set is relatively large and E-W trending. Crosscut by the Medford Dike.



gb Gabbro dikes – altered, crosscuts dolerite dikes, on west side of Middle Hill and on northern Pine Hill. Not related to Medford Dike. Neoproterozoic to Paleozoic (?).



ad Highly altered dolerite and basalt dikes – chloritic with epidote and porphyroblasts of amphibole and chlorite. Often have diffuse contacts. Possibly several ages, Neoproterozoic to Paleozoic. In Nanepahemet Fm. may have fed basalt flows in hydrothermal environments.

Dike ages (Ma)*: d 226 ± 3 (⁴⁰Ar/³⁹Ar whole rock)
 d 290 ± 15, (K/Ar whole rock)
 d 353 ± 4, (⁴⁰Ar/³⁹Ar whole rock)
 gb 402.5 ± 3 (⁴⁰Ar/³⁹Ar whole rock)
 d 573 ± 4 (⁴⁰Ar/³⁹Ar whole rock)

*some dikes experienced later thermal events

----- Large time gap in major map units. Dikes above are Neoproterozoic to possibly early Triassic -----



fq Felsic dikes with medium to coarse embayed quartz and feldspar xenocrysts – intrudes Westboro Fm. on Whip Hill, xenocrysts from coarse granite, has fluorite crystals. Neoproterozoic.



ap Gray porphyritic andesite to dacite dikes – west side of Spot Pond probably offshoot of Zst. Xenoliths and xenocrysts including embayed quartz. Neoproterozoic.

~595 Ma **Zst** Stoneham Granodiorite – granodiorite to tonalite, high mafic content, porphyritic at contacts. Age (Ma): 595.14 ± 0.17 (U-Pb CA-TIMS)

Zwap Wanapanaquin Porphyry – granodiorite porphyry. Likely branch of Stoneham Granodiorite. Neoproterozoic.

----- Straw Point volcanic rocks at Spot Pond intruded by Stoneham Granodiorite -----

Volcanic Rocks in Northern Fells at Middle Reservoir, northern Spot Pond, Wamomet Hill and further north and east (Neoproterozoic)

596-594 Ma



Zspb **Zspc** **Zspr** Straw Point Volcanic Complex – interlayered volcanic facies (bimodal):
 (Zspb) – basalt flows, tuff and sedimentary rock
 (Zspc) – welded lithic crystal tuff
 (Zspr) – rhyolite flows
 Age (Ma): 594.70 ± 0.32 (U-Pb CA-TIMS) Zspr at Middle Res.
 595.27 ± 0.34 (U-Pb CA-TIMS) Zspr at Spot Pond

Zwh Lynn Volcanic Complex at Wamomet Hill – rhyolitic tuffs and banded flows
 Age (Ma): 595.82 ± 0.23 (U-Pb CA-TIMS)

Plutonic rocks related to Lynn Volcanic Complex ~597-596 Ma



Zlwg Lawrence Woods Granophyre – porphyritic granophyre with needle-like hornblende. Likely subvolcanic to Zp and Zbj units.
 Age (Ma) - 2 zircon populations at Wrights Pond: inherited 598.13 ± 0.27 (U-Pb CA-TIMS); 596.77 ± 0.25 (U-Pb CA-TIMS). At Pine Hill: pending (U-Pb CA-TIMS).



Zdg Unnamed gabbro-diorite porphyry – intrudes Zvwq, may be related to Zrhp. Age (Ma): 596.02 ± 0.32 (U-Pb CA-TIMS)

Zrhp Rams Head Porphyry – tonalite porphyry with minor quartz and alkali feldspar, intrudes Spot Pond Granodiorite. Age (Ma): 596.24 ± 0.16 (U-Pb CA-TIMS)

--- Lawrence Woods Granophyre intrudes base of Zpmh at Pine Hill, Zpt at Wrights Pond, and Zbjc at Boojum Rock ---

Lynn Volcanic Complex in Southern Fells (Neoproterozoic).

Lynn Volcanic Complex (~597-595 Ma)



Zpt **Zpmh** Lynn Volcanic Complex - Pine Hill area:
Wright's Tower Member – crystal tuff
Middle Hill Member – volcanoclastic breccia, conglomerate, and sandstone with tuff



Facies of Lynn Volcanic Complex - Boojum Rock area:

(Zbjp) – porphyry (dike-like shape, appears to be Zlwg fissure offshoot)
 (Zbjb) – welded, banded crystal tuff
 (Zbjv) – vitric tuff
 (Zbjc) – volcanic breccia to polymictic conglomerate and sandstone (likely Zpmh equivalent)

--- Zpmh rests unconformably on Zsg ---

--- Zbjc rests unconformably on Boojum Rock Tuff ---

--- Unconformity, start of abundant embayed quartz and coarse feldspar xenocrysts in volcanic rocks, felsic dikes, and Zlwg ---



Zbrv **Zbr** **Zbrc** Boojum Rock Tuff Member – dacitic tuffs with rare fine quartz xenocrysts derived from broken quartzite in Westboro Fm.
 Zbrv - vitric tuff facies
 (- - - -) fiammé zone, dips steeply east Age (Ma): 596.35 ± 0.21 (U-Pb CA-TIMS), high in Zbrc
 Zbrl - lithic crystal tuff facies
 Zbrc – dominant, crystal tuff facies, coarser to east in Malden and Melrose

--- Zbrc rests unconformably on Zsg north of Boojum Rock and Zvwq at Pine Banks Park ---



fp Dark red to tan porphyritic (fp) rhyolite dikes west of Spot Pond – in Zsg, Zwg and Znpm, possibly several Neoproterozoic ages. At Wenepoykin Hill red dikes crosscut Zsg and are crosscut by Zrhp. Possibly related to Lynn Volcanic Complex.

Dedham Complex (609-610 Ma)



Zsg **Zsgk** **Zwg** Spot Pond Granodiorite – coarse granodiorite to granite with abundant Zlwg xenoliths and alkali granite zones/xenoliths (Zsgk). Ages (Ma): Red Cross Path - 609.46 ± 0.18 (U-Pb CA-TIMS), South of Spot Pond - 609.11 ± 0.22 (U-Pb CA-TIMS), Doleful Pond - 609.08 ± 0.24 (U-Pb CA-TIMS)

Zwg Winchester Granite – equigranular medium granite with relatively high mafic content. Plagioclase subordinate or equal to alkali feldspar. Has Zsgk xenolith like Zsg.
 Age (Ma): 609.72 ± 0.24 (U-Pb CA-TIMS)



Zwgd Quartz Diorite Xenoliths in Winchester Granite – medium-grained quartz diorite xenoliths (uncertain age).

▲ Zfi – felsite xenoliths in Zsg, unknown source and age

--- Units below intruded by Zsg, Zwg, and Zst ---



Znpm Nanepahemet Formation – hydrothermally altered and baked basalt and basalt breccia. Basal red conglomerate and sandstone and dark argillite with Westboro Fm. clasts.

----- Angular Unconformity (overlain by basal breccia/conglomerate in Nanepahemet Formation along Molly's Spring Rd.) -----

----- period of light-grade regional metamorphism -----

Westboro Fm. < 912 Ma

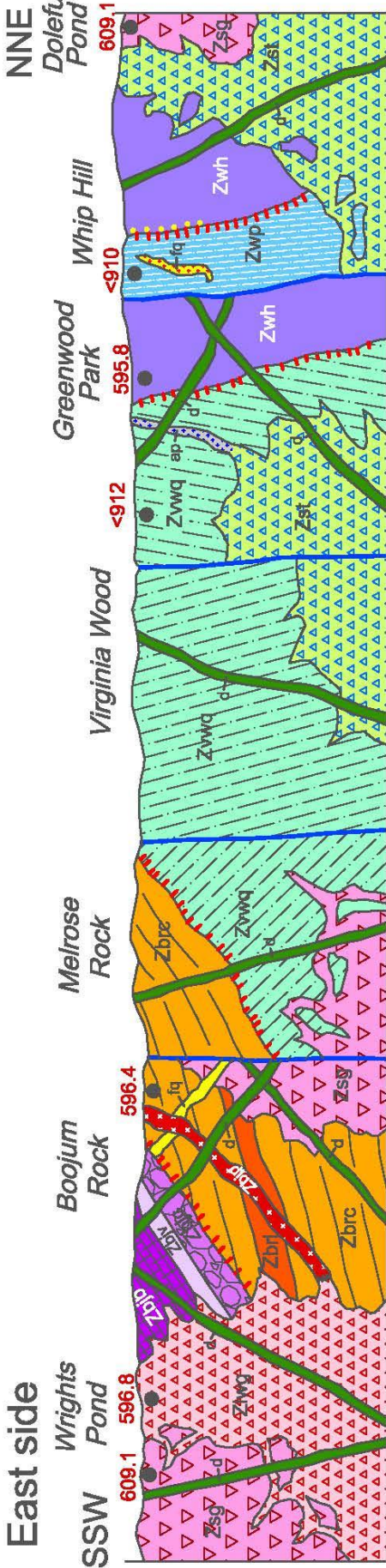
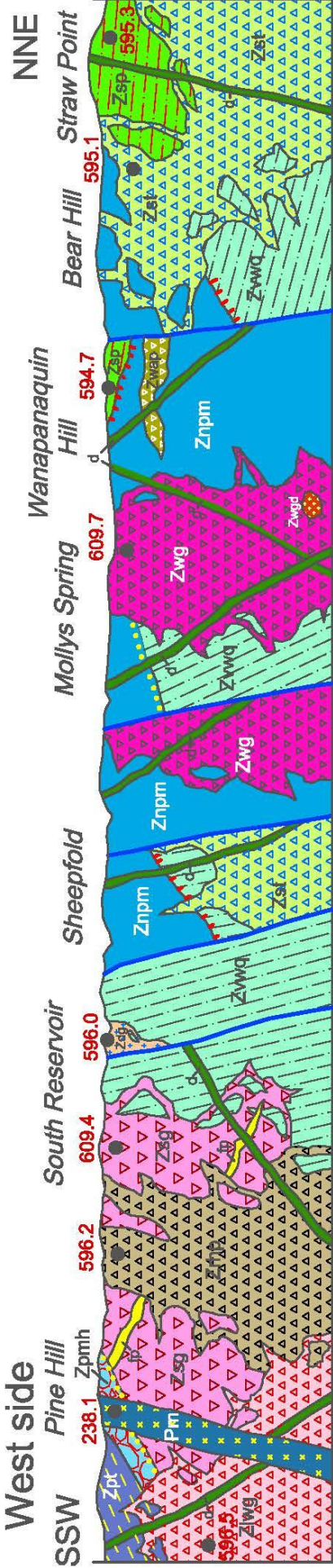


Zwp Westboro Formation in Whip Hill area – laminated mudstone, fine sandstone, and mass flow units with quartz sandstone olistoliths. Not regionally metamorphosed. Intruded by ap and fq dikes. Neoproterozoic. (LA-ICPMS, detrital zircon, quartz sandstone olistolith, <910 Ma)



Zvwq Westboro Formation in Virginia Wood and west of Spot Pond – metamorphosed and sheared, quartzite and argillite with calcium/magnesium silicate intervals. (LA-ICPMS detrital zircon: < 912 ± 0.6 Ma)

Diagrammatic cross sections showing relative age relationships of bedrock units in the Middlesex Fells.



Diagrammatic cross sections of the eastern and western sides of the Middlesex Fells Reservation intended to show the field and age relationships of the bedrock units. Geologic symbols are the same as those used on the bedrock map and in the explanation. Separate facies in the Straw Point Volcanic Complex (Zsp) are not shown. Black dots with red numbers are radiometric ages. Except for the limiting zircon ages in the Westboro Formation, all ages are CA-ID-TIMS U-Pb zircon ages. Unconformities are shown as surfaces beneath areas where either a unit above the unconformity contains fragments of the unit below that document erosion of the lower unit (yellow dots above unconformity surface) or erosion is documented beneath the unconformity as crosscutting of foliation or layering below (red tic marks beneath the unconformity).

Age Data – Units in Middlesex Fells – listed by relative age (youngest to oldest).

Medford Dike (T_{rm}): gabbro dike, crosscuts all other units including all other dolerite dikes and faults except one small (~7 cm) dike on Governor's Avenue in Medford outside the Fells and a dike mapped by Wilson (1901). Most recently obtained radiometric age: 238.07 ± 0.09 Ma (CA-ID-TIMS U-Pb zircon).

Unnamed gabbro, dolerite, and basalt dikes and their porphyritic and altered variants (gb, d, dp, ad): various ages (see below).

1. Compositional variations, degree of alteration, fault displacements, well-organized orientation sets (sets of parallel dikes of the same rock type) and crosscutting of different dike sets indicate several ages. Where exposure allows: LaForge's (1932) classification of major E-W dikes crosscutting N-S dolerite dikes is confirmed in almost all places, but there are other directions and not all dike intersections have crosscutting relationships that can be determined in the field. The youngest (E-W) dike set seems to have intruded major E-W trending faults and are crosscut by N-S trending faults. These dikes tend to be relatively thick on the order of at least 10 m.
2. Radiometric ages (in order) determined in previous works for basalt, dolerite and gabbro dikes are:

d (small) - 573 ± 5 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ whole rock),

gb - 402.52 ± 3.22 ($^{40}\text{Ar}/^{39}\text{Ar}$ whole rock),

d - 353 ± 4 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ whole rock),

d - 290 ± 15 Ma (K/Ar whole rock),

d - 226 ± 3 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ whole rock).

The ages suggest a wide variety of ages from Neoproterozoic to Mesozoic. The accuracy of these ages is not known since these dikes experienced later thermal events and many are on whole rock analyses or obtained many years ago. The dike with a radiometric age at 226 Ma is crosscut by the Medford Dike and is inconsistent with the new Medford Dike U-Pb age. The other dike ages are internally consistent with field relationships and the youngest age for E-W trending dikes. The most recently determined age for the Medford Dike suggests that the dolerite dikes can be no younger than early Triassic and are probably Paleozoic.

BIG Q: Is there a systematic composition, age, or paleomagnetic direction with dike set orientation?

Porphyritic andesitic (ap) and red to tan dacitic to rhyolitic dikes (fp, fq): mixture of at least 3 ages intruding the Boojum Rock Tuff of the Lynn Volcanic Complex (Zbrc), Spot Pond Granodiorite (Zsg), Winchester Granite (Zwg), Nanepashemet Fm. (Znpm), Westboro Formation at Whip Hill (Zwp), and the Westboro Formation in Virginia Wood (Zvwq). These dikes have not yet been found in the Stoneham Granodiorite (Zst), Lawrence Woods Granophyre (Zlwg) and Rams Head Porphyry (Zrhp), and they are crosscut by basalt/dolerite dikes. The dikes all have conspicuous chill zones. There are three main compositions: 1) gray porphyritic andesite/dacite, 2) tan to red porphyritic dacite/rhyolite, and 3) rhyolite containing many coarse embayed and rounded xenocrysts of quartz and feldspar and rounded multi-grain xenoliths from coarse granitic rocks.

1. Gray porphyritic andesite/dacite dikes in the northeast Fells along shore of Spot Pond and in Pond Street area to Whip Hill may be associated with the Stoneham Granodiorite (Zst). They primarily occur in the Westboro Formation.
2. At Wenepoykin Hill, reddish-gray porphyritic rhyolitic dikes cut through the Spot Pond Granodiorite (Zsg) and Westboro Formation (Zvwq) but are crosscut by the Rams Head Porphyry (Zrhp) indicating an age from 609-595 Ma.
3. Irregular reddish-brown porphyritic rhyolite dikes cut through the Winchester Granite (Zwg). These dikes are not aplite dikes, which have also been found in the Winchester Granite.
4. Several rhyolitic dikes with abundant coarse, embayed, and rounded quartz, plagioclase, and alkali feldspar xenocrysts as well as similar small, multi-grain xenoliths post-date a coarse granitic plutonic body in the Fells (Stoneham Granodiorite, Spot Pond Granodiorite, or Winchester Granite). These dikes have been found in the Westboro Formation at Whip Hill (Zwp), Spot Pond Granodiorite (Zsg), and Boojum Rock Tuff of the Lynn Volcanic Complex (Zbrc).
5. All felsic dikes are cut by the basalt and dolerite dikes in the Fells indicating that the felsic dikes are older and likely associated with a Neoproterozoic plutonic body.

BIG Qs: How many ages and what are the ages, origins and sources relative to granitic plutons?

Wanapanaquin Porphyry (Zwap): Porphyritic tonalite to granodiorite, sometimes with orange color due to hematite or other iron oxide stain in its matrix. Only occurs on Wanapanaquin Hill. Same composition as Stoneham Granodiorite (Zst) but has rusty orange color. Has less alkali feldspar than the Winchester Granite (Zwg).

- 1) Appears to be a porphyritic branch of the Stoneham Granodiorite (Zst) west of a major fault that runs along the west flank of Bear Hill. Similar in texture to contact areas of the Stoneham east of the fault. This would be the only area of the Stoneham west of the Bear Hill fault.
- 2) Cuts across the Nanepashemet Formation (Znpm).
- 3) Cut by dolerite dikes (d) and altered dolerite dikes (ad).

Stoneham Granodiorite (Zst): Mostly equigranular granodiorite to tonalite. Porphyritic in chill zones. Contains altered plagioclase with clean rims. Higher mafic content than other large granitic intrusive bodies in the Fells. Orangish color in places is due to iron oxide in matrix. Has less alkali feldspar than the Winchester Granite (Zwg).

- 1) Unit has abundant inclusions from: 1) the Westboro Fm. (Zvwq), both white quartzite and argillite hornfels and 2) basalt hornfels of the Nanepashemet Formation (Znpm) and Straw Point Volcanic Complex (Zspb), all of which it intrudes. Inclusions are especially abundant on Deer Hill and its Rt. 93 roadcut, on islands in northwest Spot Pond, and along Pond Street northwest of Spot Pond.
- 2)) The chill zone contact where it intrudes the Straw Point Volcanic Complex (Zspr) at the small peninsula forming the east side of the northwest cove of Spot Pond has large rhyolite inclusions from the Straw Point Volcanic Complex (Zspr).
- 3) Unit appears to have a roof pendant of hornfels of the Westboro Fm. (Zvwq) on Deer Hill and at Sheepfold, and of the Nanepashemet Fm. (Znpm) at Sheepfold and further north on Winthrop and Bear Hills and on Taylor Mountain.
- 4) Probably feeds the Wanapanaquin Porphyry (Zwap).
- 5) Separated from Winchester Granite (Zwg) by a major fault on the west side of Bear Hill.
- 6) The only other plutonic body with which the Stoneham has a visible contact is the Spot Pond Granodiorite (Zsg) near Doleful Pond and Stoneham High School. Intrusion into the Westboro Fm. at Whip Hill (Zwp) seems likely, but no visible contact has been found and this may be a fault contact concealed by wetlands north of Whip Hill.
- 7) This unit appears to underlie much of the northern half of Spot Pond and is likely the source of gray andesite to dacite dikes (ad) on Whip Hill and along Pond Street in Stoneham.
- 8) The Stoneham has a contact with much assimilation of the Westboro Formation along the shore of Spot Pond at the south end of the Stoneham Zoo parking lot and along nearby Pond Street.
- 9) U-Pb age: 595.08 ± 0.17 Ma (zircon, CA-ID-TIMS) from Pond Street northwest of Spot Pond. Slightly younger than the Lynn Volcanic Complex at Wamoset Hill and slightly younger than the Straw Point Volcanic Complex at Middle Reservoir and it intrudes the Straw Point at the north end of Spot Pond. This unit is too young to be associated with the Dedham Complex (Spot Pond Granodiorite and Winchester Granite).

Volcanic Rocks in the Northern Fells

Straw Point Volcanic Complex (Zspr, Zspc, Zspb): These units form a gently dipping (nearly horizontal) bimodal volcanic sequence at the northwest corner of Spot Pond (Straw Point) including sialic (Zspr, Zspc) and basalt flows interbedded with contorted and coarse to fine basaltic sediment and tuff (Zspb). A banded rhyolite flow at the north end of Middle Reservoir is mapped with this unit. Basaltic units (and its bimodal character) make it unique among volcanic units of similar age with Lynn Volcanic Complex in the Fells. Extensive outcrop area north and northeast of the Fells as seen in studies by Smith and Hon (1984), Smith (1985), Cardoza (1987), and Cardoza et al. (1990).

- 1) At the northeast corner of Middle Reservoir low-angle banded felsic lava and layered pyroclastic units sit on an angular unconformity over steeply dipping beds in hornfels and conglomerate of the Nanepashemet Formation (Znpm).
- 2) Intruded by Stoneham Granodiorite (Zst) at Straw Point and northeast corner of Dark Hollow Pond.
- 3) Contains embayed and rounded quartz xenocrysts from a medium to coarse granodiorite and granite (likely Zsg or Zwg).
- 4) Unlike the Lynn Volcanic Complex, it has a basaltic component (bimodal composition) at Straw Point. It is entirely felsic at the north end of Middle Reservoir, but this is a small outcrop area and slightly younger than parts of the unit at Spot Pond. Pyroclastic units at Straw Point (Zspc) have basaltic lithic fragments.
- 5) U-Pb age: Zspr at Middle Reservoir is 594.70 ± 0.32 Ma (zircon, CA-ID-TIMS). This is slightly younger than ages for the Lynn Volcanic Complex (Wamoset Hill) and Stoneham Granodiorite in the Spot Pond area. The radiometric age at Middle Reservoir is statistically indistinguishable from the Stoneham Granodiorite that intrudes the Straw Point units at Straw Point.
- 6) U-Pb age: Zspr at the north end of Spot Pond is 595.27 ± 0.34 Ma (zircon, CA-ID-TIMS).

Q1: Are these units part of the Lynn Volcanic Complex or a separate volcanic unit? Similar in age but from a different eruption center?

Volcanic Rocks in the Northern Fells (cont.)

Lynn Volcanic Complex from east of Whip Hill Park to north end of Spot Pond

(Zwh): Welded and non-welded crystal and lithic tuffs and banded rhyolite forming tuff and lava flows. Pyroclastic units contain embayed quartz crystals. No basaltic lithic fragments have been found in these units.

- 1) The unit's upper surface is in fault contact with the Westboro Formation at southern Whip Hill (Zwp).
- 2) Contains quartzite and argillite lithic fragments from the Westboro Fm. (Zvwq and Zwp).
- 3) Contains embayed and rounded quartz xenocrysts from medium to coarse granite or granodiorite (Zwg, Zsg). (Too old for the Stoneham Granodiorite (Zst) to be included.
- 4) Unconformably overlies the Westboro Fm. of Virginia Wood (Zvwq) on Wamoset Hill and in Sewall Woods Park along the Lynn Fells Parkway outside the Fells. Unit does not have the metamorphic grade or fabric of the Westboro Fm. in Virginia Wood (Zvwq)
- 5) It has strictly felsic (rhyolitic) components unlike the Straw Point Volcanic Complex at the north end of Spot Pond which has felsic and basaltic components.
- 6) U-Pb age at Wamoset Hill: 595.82 ± 0.23 Ma (zircon, CA-ID-TIMS). This age is younger than the Spot Pond Granodiorite and Winchester Granite by about 13 Myr but only slightly older than the Stoneham Granodiorite and Straw Point Volcanic Complex at Middle Reservoir and Spot Pond. This unit is slightly younger than the Boojum Rock Tuff (Zbrc) of the Lynn Volcanic Complex in the southeastern Fells.

BIG Q1: This unit is similar to the Lynn Volcanic Complex in the southern Fells except that it has flow units. How are they related?

Q2: How is this unit related to members of the Lynn to the East (Smith, 1985; Smith and Hon, 1984)?

Lawrence Woods Granophyre (Zlwg): Pinkish-gray to gray granophyric porphyry with euhedral phenocrysts of plagioclase, embayed quartz, granophyric grains of fine alkali feldspar and quartz, and needle-like amphibole phenocrysts. Subvolcanic intrusive unit that appears to be associated with the Lynn Volcanic Complex as found further east (Smith and Hon, 1984; Smith, 1985). In current mapping outside the Fells other granophyres that are subvolcanic units associated with the Lynn are lumped into this unit.

- 1) Intrudes and has chill zone against Lynn Volcanic Complex at Boojum Rock and Wrights Pond (Zbjc and Zbjb) and in the Pine and Middle Hill areas (Zpmh and Zpt).
- 2) Intrudes and has chill zone against Spot Pond Granodiorite (Zsg) in Lawrence Woods, Pine, Little Pine, and Middle Hill areas, and near Boojum Rock.
- 3) Intrudes and has chill zone against the Rams Head Porphyry (Zrhp) at the entrance to Medford High School. This is contrary to U-Pb zircon ages for the Lawrence Woods and Rams Head, but just barely and not statistically (see #7 below).
- 4) Contains xenolith of Zpt in valley along west side of fault west of Middle Hill.
- 5) Has a peculiar contact zone with the Lynn Volcanic Complex (Zpt) on Pine Hill that makes the Lynn look porphyritic along the contact. The volcanic rock appears to be recrystallized along the contact.
- 6) Has an inclusion of what appears to be from the Rams Head Porphyry (Zrhp) south of South Border Road near Lawrence Memorial Hospital in Lawrence Woods. This is contrary to U-Pb zircon ages for the Lawrence Woods and Rams Head, but just barely and not statistically (see #7 below).
- 7) U-Pb (zircon, CA-ID-TIMS) ages (2 populations, 3 crystals each, both possibly inherited): 598.13 ± 0.27 Ma; 596.77 ± 0.25 Ma from Elm Street in North Medford. U-Pb (zircon, CA-ID-TIMS) age (population of 3 crystals plus several much older crystals): 596.50 ± 0.53 Ma at Pine Hill on west side of Rt. 93. Unit shows field evidence of being younger than the Rams Head Porphyry (see #5 and #6 above). Ages could be too old due to prolonged crystal growth and some inherited grains.
- 8) Since ages of Zlwg and Zrhp are close they may be separate but closely related magma pulses. These units are too young to be part of the Dedham Granodiorite (Spot Pond Granodiorite and Winchester Granite) by about 13 Myr.

BIG Q: How is the Lynn Volcanic Complex at Pine Hill related to the Lawrence Woods Granophyre? Are they co-magmatic? Is the Lawrence Woods intruding its own volcanic deposits?

Rams Head Porphyry (Zrhp): Porphyritic, highly plagioclase-dominated tonalite to quartz diorite porphyry with very low alkali feldspar content.

- 1) Unit has a chill zone and partly assimilated inclusions in contact with the Spot Pond Granodiorite (Zsg) just west of Rt. 93 near Wenepoykin Hill and at the southern end of South Reservoir. Inclusions are well exposed at the point on the west side of the small eastern embayment at the south end of South Reservoir.
- 2) Has an inclusion in the Lawrence Woods Granophyre (Zlwg) in Lawrence Woods but this is contrary to U-Pb zircon ages, but just barely and not statistically (see item #7 of the Lawrence Woods Granophyre above.)
- 3) Crosscuts reddish-colored rhyolite dikes that cut across the Spot Pond Granodiorite on Wenepoykin Hill.
- 4) U-Pb zircon (CA-ID-TIMS) age: 596.24 ± 0.16 Ma. Age close to (slightly younger than) Lawrence Woods (Zlwg). Field relationships indicate an age older than the Lawrence Woods. This age and the more dioritic composition of the unit strongly suggest that the Rams Head may be co-magmatic with the Boojum Rock Tuff (Zbrc) of very similar age.

Zdg: A sliver of diorite-hornblende gabbro in the southwestern Fells. This unit has not been recognized previously. The unit has <2% quartz (possibly melted inclusions from intruded Westboro Fm.) and no alkali feldspar with 45% plagioclase and 55% amphibole (hornblende). Therefore, it does not resemble any granitic plutonic unit in the Fells.

- 1) The north side of the diorite-gabbro exposure is an intrusive contact with the Westboro Formation (Zvwq).
- 2) The south side of the body is truncated along a major E-W trending fault.
- 3) U-Pb age: 596.02 ± 0.32 Ma (zircon, CA-ID-TIMS).

Volcanic Rocks in the Southern Fells

Lynn Volcanic Complex in the Pine Hill area, 2 distinct members (Zpt, Zpmh):

Zpt (upper unit – Wrights Tower Tuff Member) - welded to non-welded crystal and lithic tuffs of Pine and Middle Hills and at eastern Wrights Pond. Rests on Middle Hill Member.

Zpmh (lower unit – Middle Hill Member) – basal volcanoclastic rocks with quartz and alkali feldspar crystals, clasts derived from Spot Pond Granodiorite (Zsg), and volcanic and quartzite/argillite hornfels lithic fragments from Westboro. Includes greenish-gray diamictite basal units on Middle Hill. Matrix is mostly a poorly sorted volcanoclastic sandstone/conglomerate. Likely equivalent to the Zbjc facies of the Lynn Volcanic Complex in the Boojum Rock area.

1. Zpt inclusion in Lawrence Woods Granophyre (Zlwg) west of fault on west side of Middle Hill.
2. Zpt and Zpmh intruded by Lawrence Woods Granophyre (Zlwg) on southern Pine, Little Pine and Middle Hills, and at Wrights Pond with chill zone in Zlwg. The age difference is likely very small, and the two units are related.
3. Zpmh has granite debris from the Spot Pond Granodiorite (Zsg) in volcanoclastic conglomerates on Middle, Little Pine, and Pine Hills and west of Middle Hill.
4. Quartzite lithic fragments and clasts (some with flattened and sutured, but also some with intact, round grains) from the Westboro Formation at both Virginia Wood (Zvwq) and Whip Hill (Zwp), and abundant volcanic lithic fragments of a variety of types in Zpt and Zpmh.
5. Sampling for a U-Pb age was not attempted because of abundant lithic fragments from older units and no flows were found.

BIG Q1: How is this unit related to the Lynn and Straw Point Volcanic Complexes in the northern Fells? Similar lithologies as Lynn Volcanic Complex at Wamoset Hill except for the banded rhyolitic flows at Wamoset Hill.

BIG Q2: What are its equivalent units further east in the Lynn Volcanic Complex (see members of Smith and Hon, 1984 and Smith, 1985)?

Volcanic Rocks in the Southern Fells (cont.)

Facies of Lynn Volcanic Complex in Boojum Rock area (Zbjv, Zbjb, Zbjc, Zbjp): occurs at northeast corner of Wrights Pond and on Boojum Rock as far east as the MIT Observatory. Above the basal clastic unit (Zbjc) these volcanic units tend to have a pale reddish to purplish color.

Zbjv - ultra fine-grained chert-like vitric tuff with very small crystals that are hard to detect in outcrops.

Zbjb - mixture of pyroclastic banded and welded crystal to lithic tuffs with a dark purplish-gray color and in some places very well preserved primary volcanic structures such as pyroclastic banding and fiammé. Includes areas that look like coarse dark gray porphyry but are a highly welded crystal tuff. Also has patches of reddish volcanic breccia like in unit below. At northeast corner of Wrights Pond includes dark reddish-black welded and banded tuff with varying crystal and lithic fragment concentrations.

Zbjc - Unit grades upward, first as volcanic breccia with highly angular red volcanic clasts and then into much better sorted rounded-pebble, polyimictic conglomerate. The matrix of this unit is a poorly sorted greenish-gray sandstone. Clasts are volcanic (conspicuously dark red), quartzite, alkali granite (possibly Ball Quarry Granite of Smith and Hon, 1984 and Smith, 1985), red sandstone, and interbedded argillite and fine sandstone.

Zbjp - traceable dike-like zone of reddish- to pinkish-gray porphyritic rhyolite with non-broken, euhedral and cumuloxyphic plagioclase crystals and sparse lithic fragments. Has flow-banded zones and thinner volcanoclastic zones with rounded volcanic clasts along its contacts with the Boojum Rock Tuff (Zbrc). Has not been found south of a large E-W trending dolerite dike on Boojum Rock.

Contacts and continuity of the facies are hard to trace because of intense shearing and dismemberment of rock units east of the Quarter Mile Pond Fault along Woodland Road. Thus, no formal members have been distinguished in this area.

- 1) Breccia and conglomerate of Zbjc rest on an unconformity on the Boojum Rock Tuff (Zbrc) near the MIT Observatory and the Spot Pond Granodiorite (Zsg) near Woodland Road.
- 2) Basal unit contains granite pebbles and boulders including red alkali granite, possibly from the Ball Quarry Granite to east (Smith and Hon, 1984; Smith 1985), and abundant quartz grains, which are much smaller and rare in the underlying Boojum Rock Tuff (Zbrc). Basal unit is an olive-green volcanoclastic diamictite to poorly sorted sandstone like found in the basal unit of the Lynn Volcanic Complex (Middle Hill Member, Zpmh) in the Pine Hill area.
- 3) Intruded by Lawrence Woods Granophyre (Zlwg) along Woodland and East Border Roads. In some places the base has an intensely reddish-brown color suggestive of oxidation by weathering or oxidation related to contact metamorphism near its contact with the Lawrence Woods.
- 4) Well preserved volcanic structures: units with banding and flattened pumice with rapid facies changes.
- 5) Many dark reddish- to purplish-gray to reddish-brown banded tuff and crystal tuff lithic fragments.
- 6) Red porphyritic rhyolite unit (Zbjp) seems to form a fissure cutting across the Boojum Rock Tuff (Zbrc), likely as a branch of the Lawrence Woods Granophyre (Zlwg).

Boojum Rock Tuff Member of the Lynn Volcanic Complex (Zbrc, Zbrl, Zbrv): dacitic to andesitic crystal and lithic tuff that is dark greenish-gray on fresh faces with a dominance of broken plagioclase crystals (up to 50% of rock), scattered hornblende crystals in various states of alteration, and rare, tiny, broken quartz crystals (xenocrysts from quartzite). All units have steeply eastward-dipping features. Unit contains no coarse embayed quartz crystals like all younger felsic volcanic units in the Fells.

Zbrv - an area of vitric, faintly-banded tuff on the southeastern side of the Fells that has very small crystals that are difficult to detect in outcrops.

Zbrl - traceable zone of lithic crystal tuff within Zbrc that has volcanic and quartzite lithic fragments, some up to 10 cm across. A fiammé zone occurs at the top (eastern side) of this unit.

Zbrc - crystal tuff occurring over a wide area in the southeastern Fells.

Entire unit is massive and pyroclastic with no flows or intrusive component.

- 1) Volcanic (felsic) and quartzite/argillite lithic fragments but no granitic fragments or debris.
- 2) Has only rare, fine-grained, angular and broken quartz fragments that are xenocrysts from the Westboro Fm., and unlike all other felsic volcanic units in the Fells it has no coarse embayed or resorbed quartz inherited from granitic plutonic bodies.
- 3) Subtle cleavage-like fractures that are not found in the younger volcanic units suggest a period of light deformation not experienced by the younger units. This deformation is associated with slickensided surfaces that have hematite mineralization and epidote veins, especially near the MIT Observatory on Boojum Rock.
- 4) Basal breccias and conglomerates of the Lynn Volcanic Complex at Boojum Rock (Zbjc) lie unconformably on the Boojum Rock Tuff near the MIT Observatory.
- 5) U-Pb age on zircon crystals (Zbrc) near Pinnacle Rock: 596.35 ± 0.21 Ma (CA-ID-TIMS). This date is from high in the tuff unit in its youngest part. The chemistry of this unit is dacitic to andesitic and its age is like the age of the Rams Head Porphyry (Zrhp) that may be subvolcanic to the tuff.
- 6) The Boojum Rock Tuff may unconformably overlie the Westboro Fm. (Zvwq) south of Virginia Wood, but this contact is concealed by glacial sediment. Further east in Malden and Melrose at Pine Banks Park and in the East Wyoming Ave area of Melrose the Boojum Rock Tuff unconformably overlies the Westboro Formation.
- 7) A contact with the Spot Pond Granodiorite (Zsg) is exposed east of Woodland Road, but age relationships are hard to interpret and are revealed only by radiometric ages in both units, which indicate the Spot Pond is older. No granite debris has been found in the base of the Boojum Rock. It appears that the Boojum Rock unconformably overlies the Spot Pond because the contact is too irregular to be a fault.
- 8) The Boojum Rock Tuff is unconformably overlain by other units of the Lynn and is interpreted to be the basal unit of the Lynn in the Fells area and further east in Malden and Melrose.

Spot Pond Granodiorite (Zsg): coarse mostly granodiorite with minor granite and tonalite. Has perthitic alkali feldspar and a high quartz content. Plagioclase dominates feldspar. This rock type is the “ideal” Dedham Granodiorite and is considered here to be a part of the Dedham (Granodiorite) Complex but previous works (Kaye, 1980; Smith and Hon, 1984; Smith, 1985) lumped it into the Dedham with three other units, the Lawrence Woods Granophyre (Zlwg), Rams Head Porphyry (Zrhp), and Stoneham Granodiorite (Zst) that are now known to be younger by at least 13 Myr.

- 1) Rare inclusions of felsic volcanic rock (Zfi) of uncertain origin and age are in the unit.
- 2) An indistinct contact with the Boojum Rock Tuff Member of the Lynn Volcanic Complex (Zbrc) is exposed east of Woodland Road and west of the Fells Reservoir, but age relationships are hard to interpret and are revealed only by radiometric ages in both units, which indicate the Spot Pond is older. No granite debris has been found in the base of the Boojum Rock. It appears that the Boojum Rock unconformably overlies the Spot Pond.
- 3) Abundant large inclusions of the Westboro Fm. (Zvwq) are found in the Spot Pond at the south end of Spot Pond, along Rt. 28, and west of Rt. 93 to the Winchester Reservoirs. These inclusions and Zsg get truncated along contacts with the Lawrence Woods Granophyre (Zlwg) and Rams Head Porphyry (Zrhp).
- 4) The contact area with the Westboro Fm. west of Rt. 93 has a well-defined vertical foliation paralleling the contact with the Westboro Formation (Zvwq) and paralleling a major E-W fault. The foliation is interpreted to be the result of shearing of weak (warm) granodiorite, but not associated with the fault. The fault has brittle fracturing that allowed deep glacial erosion of the fault zone and it displaces dolerite dikes that cut the foliation in the granodiorite. Therefore, the fault appears to be younger than foliation in the granodiorite. Magnetic susceptibility shows a well-defined lineation that indicates shear in the foliation plane with an east-west trend (i.e., horizontal shear on the nearly vertical foliation plane).
- 5) Pieces of Zsg occur in the Lynn Volcanic Complex (Zpmh) that rests on an unconformity on the Spot Pond on Pine, Little Pine, and Middle Hills.
- 6) Contains areas of leucocratic alkali granite (Zsgk). Are these xenoliths or alkali enclaves? They resemble the Ball Quarry Granite (Smith and Hon, 1984; Smith, 1985) to the east and alkali feldspar syenite that outcrops north of the Fells and occurs as glacial erratics.
- 7) U-Pb ages: near Red Cross Path is 609.45 ± 0.25 Ma (zircon, CA-ID-TIMS), south of Spot Pond is 609.11 ± 0.22 Ma (zircon, CA-ID-TIMS), and near Doleful pond is 609.08 ± 0.24 Ma.

BIG Q1: What is the source of the felsic volcanic inclusions (Zfi)?

BIG Q2: Are the alkali granite blocks xenoliths or crystallization enclaves?

Winchester Granite (Zwg): Dark reddish- to orangish-pink, alkaline appearing, medium-grained, equigranular mostly granodiorite with secondary granite and tonalite. In places has red-colored K-spar and elongate lenticular pinkish-red rhyolite dikes. Unit is never porphyritic, even in contact areas. This rock type is finer than the “ideal” Dedham Granodiorite in the Spot Pond Granodiorite (Zsg) but is part of the Dedham Complex. Previous works (Kaye, 1980; Smith and Hon, 1984; Smith, 1985) lumped it into the Dedham with other units now known to be younger: the Rams Head Porphyry (Zrhp) and Stoneham Granodiorite (Zst). The unit is more alkaline than either of these units.

- 1) Intrudes the Nanepashemet Formation (Znpm) over a wide area of the northwest Fells creating basaltic hornfels in the Nanepashemet. Along the contact the Nanepashemet may recrystallize to amphibolite with coarse hornblende crystals.
- 2) Dark orangish-red, very fine chill zone along contact with the Nanepashemet at the north end of Middle Reservoir.
- 3) Intrudes the Westboro Fm. (Zvwq) with relatively smooth intrusive contact over long distances and sparse Westboro xenoliths.
- 4) Has many light-colored rhyolite dikes (fp) that do not occur in the Stoneham Granodiorite (Zst).
- 5) Separated from Stoneham Granodiorite by a major fault at the west side of Bear Hill and does not share a contact with the Stoneham.
- 6) Contains xenoliths or enclaves (?) of alkali granite (mapped as Zsgk like in Spot Pond) and a large xenolith of quartz diorite (Zwgd) on Money Hill in Winchester. This unit, because of its quartz content, does not appear to be related to rock that is more mafic and assimilated into the Winchester Granite (next item).
- 7) At the northeastern corner of North Reservoir there are areas of highly assimilated mafic rock that gives the Winchester a mafic appearance and reduced quartz content. These areas are mapped as part of the granite.
- 8) U-Pb age east of Long Pond: 609.72 ± 0.24 Ma (zircon, CA-ID-TIMS). This age is significantly older than the Straw Point and Lynn Volcanic Complexes.

Nanepashemet Formation (Znpm): Altered dark (almost black) to medium gray to greenish-gray basalt hornfels, dark greenish-black baked, basaltic fine sediment to breccia, basaltic tuff, and volcanic-pebble conglomerates all baked. Unit appears massive in outcrop and is usually hornfels because of alteration near Stoneham Granodiorite (Zst), Winchester Granite (Zwg), and mafic dikes (d, dp). Amphibolite due to recrystallization in some contact areas that sometimes has garnet. It has a quartzite-bearing gray conglomerate/breccia and red to black laminated sandstone/mudstone in its base along Molly's Spring Road. It has baked, mafic volcanic pebble conglomerate (with a few felsic pebbles) and a marble (skarn) unit at the north end of Middle Reservoir.

- 1) Unit overlies the Westboro Formation (Zvwq) along the north side of Molly's Spring Road. This contact is rarely exposed due to faulting and intrusions. There is a change in metamorphic grade across the contact and truncation of regional metamorphic foliation below in the Westboro Formation. The base of the unit contains conglomerate, breccia, and mudstone with clasts from the Virginia Wood and occasionally well-preserved sedimentary layering that has not been altered by metamorphism.
- 2) Unconformably overlies the Westboro Fm. (Zvwq) at the south end of Sheepfold where both rock units have been baked to hornfels by intrusion of the Stoneham Granodiorite (Zst).
- 3) At the north end of Middle Reservoir steep bedding in hornfels is truncated by gently dipping layering in rhyolitic pyroclastic and flow units in the Straw Point Volcanic Complex (Zspr) indicating an unconformity.
- 4) Structures in this unit are recrystallized and obscured by contact metamorphism across most of the Fells, forming mostly a basaltic hornfels with abundant epidote and chlorite.
- 5) Radiometric ages cannot likely be obtained from this unit. It post-dates the Westboro Formation (Zvwq) (less than ~910 Ma) and is intruded by the Winchester Granite at ~610 Ma and these are the only numerical constraints on its age.

Mapping has reinterpreted areas previously mapped as quartz vitrophyre and vitrophyre by Kaye (1980) as basaltic hornfels. No basaltic flow or pillow structures or vesicular units have been found in the Fells although amygdaloidal basalt pebbles occur in the unit's breccias and conglomerates. Previously, the Nanepashemet Formation and the Straw Point Volcanic Complex of this map were mapped together as the Middlesex Fells Volcanic Complex, but new radiometric ages make it impossible that they are part of a single unit.

BIG Qs: In what tectonic environment did this unit form? How can we date basalt in this unit?

Westboro Formation on Whip Hill (Zwp): Gray, laminated to massive, rusty-weathering mudstone, siltstone, and fine sandstone with light to medium gray sandstone olistoliths with soft-sediment deformation in muddy mass flow units. The olistoliths have pinched ends and extremely round, medium sand grains that are not sutured, and have no indication of metamorphism. The sand grains are almost exclusively quartz. The whole unit has no foliation resulting from regional metamorphism. Has well preserved laminated bedding that strikes ~E-W and dips steeply (+75° in most places with some slightly overturned) with up to north. Unit has ripple crossbeds and cut and fill structures. Laminated mudstone and siltstone with preserved bedding has a strong anisotropy of magnetic susceptibility (AMS) foliation at a low angle to bedding but a weak lineation that suggests a sedimentary fabric. Could be a candidate for a paleomagnetic pole position if not rotated or overprinted by local intrusions and volcanic rocks.

This part of the Westboro Formation is separated in mapping from the rest of the Westboro because of several characteristics that are different than the Westboro in other areas.

A. The unit has well preserved bedding and sedimentary structures.

B. The unit is not regionally metamorphosed and has no cleavage. Sand grains are very well rounded and not flattened and sutured. Hornfels does occur in the unit near intrusions.

C. The unit has no calcium-magnesium silicate zones resulting from a dolomitic composition.

1) Includes a small contact area with volcanic rock of the Lynn Volcanic Complex at north end of Whip Hill. This contact is very irregular, is not a fault surface, and indicates that the volcanic rock lies unconformably on the unit.

2) Its southern boundary is a fault contact with the Lynn Volcanic Complex (Zwh) in a fault block to the south.

3) Unit is heavily baked by Stoneham Granodiorite (Zst) in some areas forming a hornfels, especially along the northeast shore of Spot Pond next to the Stone Zoo.

4) U-Pb zircon ages (LA-ICPMS) on 210 zircon grains from a quartz sandstone olistolith on Whip Hill indicate a maximum age of ~910 Ma and an age distribution identical to other parts of the Westboro Formation in Virginia Wood and further east outside the Fells.

BIG Q: This appears to be an unmetamorphosed section of the Westboro Formation. How did this happen?

Westboro Formation (Zvwq): interlayered white to dark gray quartzite and foliated siliceous argillite with areas of calcium/magnesium silicate rocks containing tremolite, diopside, calcite, and zoisite. Unit has mylonitic and necked quartzite layers and units with highly stretched and flattened, sutured, and polycrystalline quartz grains with muscovite tails and shadows in some places. Has preserved bedding in isolated places with a bedding parallel metamorphic foliation and a well-developed AMS (anisotropy of magnetic susceptibility) foliation with a weak lineation indicating flattening parallel to bedding (pure shear). Small scale folds of the unit's foliation occur in a few places but are most common in calcium/magnesium-silicate units.

- 1) Unit is metamorphosed with a distinct metamorphic fabric not seen in any other unit in the Fells except for one zone in the Spot Pond Granodiorite (Zsg).
- 2) On Wamoset Hill, foliation is truncated by an unconformity with the overlying Lynn Volcanic Complex (Zwh).
- 3) Forms large xenoliths in the Spot Pond Granodiorite (Zsg).
- 4) Forms lithic fragments in the Boojum Rock Tuff of the Lynn Volcanic Complex (Zbrc) and all younger volcanic units.
- 5) Has the same zircon age population as quartzites further east near Breakheart Reservation in the Westboro Formation (Thompson et al., 2012). Detrital zircon crystals yielded a youngest U-Pb age of 909 +/-24 Ma (LA-ICPMS; F. MacDonald, pers. com.) with the youngest zircon being 912 ± 0.6 Ma (CA-ID-TIMS, F. MacDonald, per. com.)
- 6) Occurs as pebbles in the base of the Nanepashemet Formation west of South Reservoir along Molly's Spring Road.